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13. ABSTRACT (Maximum 200 Words)  The research described in this final report continues, and greatly extends our ongoing investigations of basic, elemental, cognitive processes in humans. During the period covered by the report we focussed on validating the original dimensional overlap model (DO-'90: Kornblum, Hasbroucq & Osman, 1990), testing some of its fundamental predictions, and recasting the model itself in a computational form. These effort appear to have been successful. The original model and its taxonomy have become an effective integrative framework in an important domain of human performance (stimulus-stimulus, and stimulus-response compatibility in the broadest sense of these terms), and encompass, in a principled manner, a broad family of performance tasks representing classic problems in human cognition (e.g., Stroop and Stroop-like tasks, Eriksen and Eriksen-like paradigms, and Simon and Simon-like effects). Our work has resulted in the publication of 10 peer reviewed articles, with 4 manuscripts presently under review, one dissertation, and 17 presentations at professional meetings. The model has also contributed an important theoretical perspective to investigators working on psychophysiological and neurophysiological mechanisms of response production, and stimulus-response association processes. The principal goal for our future work is to develop and extend the model further, and test its new properties and implications. Some of these new properties span inter- as well as intra-trial phenomena, and mark the beginnings of the theoretical and empirical bridges that we were hoping, originally, to be able to build between the family of SRC tasks, and the central problems of cognition.			
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## I. INTRODUCTION

The research described in this report includes some of our past as well as some of our presently ongoing investigations of basic, elemental, cognitive processes in humans. During the grant period just concluded, we focussed on validating the original dimensional overlap model (DO-'90: Kornblum, Hasbroucq & Osman, 1990), testing some of its fundamental predictions, and recasting the model itself in a computational form. All these effort appear to have been successful. The original model and its taxonomy have become an effective integrative framework in an important domain of human performance (stimulus-stimulus, and stimulus-response compatibility in the broadest sense of these terms), and encompass, in a principled manner, a broad family of tasks representing classic problems in human cognition (e.g., Stroop and Stroop-like tasks, Eriksen and Eriksen-like paradigms, and Simon and Simon-like effects). The model has also contributed an important theoretical perspective to investigators working on psychophysiological and neurophysiological mechanisms of response production, and stimulus-response association processes (e.g. aside from our own work over 20 citations to Kornblum et al. 1990, have appeared during the past 12 months alone in psychophysiological or neurophysiological journals). The principal objective for our future work is to develop and extend the model further, and test its new properties and implications. Some of these new properties (DO-'97: see Kornblum, et al, under review) mark the beginning of the theoretical and empirical bridges that we originally were hoping to be able to build between the family of SRC tasks and the central problems of cognition.

At the core of the model, both the original (DO-'90) and the more recent computational version (DO-'97), is the idea that when a stimulus-response ensemble produces either high or low compatibility effects it is because the stimulus and response sets have important characteristics in common. We have called this the *dimensional overlap* between sets, and defined it as the degree to which stimulus and response sets are perceptually, structurally, or conceptually similar. At the functional level, the model includes two major processing stages: *stimulus encoding* and *response production*. These stages are further broken down into sub-processes. Given that the stimulus and response sets in an ensemble have dimensional overlap, the model postulates that elements of the stimulus set automatically activate corresponding elements in the response set. If the activated response is the required one, it will be executed rapidly and correctly; if it is not, then it will be relatively slow and error prone. Dimensional overlap can occur between relevant, and irrelevant dimensions of the stimulus and response sets, or just the stimulus set. These various combinations form the basis of the model's taxonomy that includes many of the experimental paradigms being used to study attentional, perceptual, and categorization processes.

While DO-'97 has retained the *conceptual framework* developed in DO-'90, the fundamental *nature* of the model has been altered from an information processing flow chart (see Figure 1) to a full fledged computational model with a PDP architecture (see Figure 2). DO-'97 now includes temporal dynamic properties that DO-'90 did not have, and that greatly extend the power and scope of the model. In particular, processing in the stimulus encoding and response production stages are represented as activation growth functions that terminate when the activation level reaches *threshold* for that particular stage. As activation builds in the first stage, the second stage is clamped to zero; the stages are thus discrete and serial-in nature. However, their effects are not additive in the AFM sense (Sternberg, 1969), but *predictably* interactive (see Kornblum et al., under review, and section II.C). After reaching threshold, the activation levels decay back to, or even below, zero. Overlapping stimuli and/or responses are connected by automatic activation lines, whether they are relevant or not. Together, these new properties enable DO-'97 to account in a *quantitative* way for the principal performance characteristics of all eight tasks in the DO taxonomy – something that DO-'90 was able to do in a qualitative, or at best, ordinal way – and to predict some of the distributional characteristics of such performance. In addition, DO-'97 is able to deal with such *direct* temporal variables as SOA, and relatively *indirect* temporal consequences of other variables such as stimulus similarity. Finally, while DO-'90 was restricted to *intratrial* effects, these new properties permit DO-'97 to make predictions about *inter-trial* effects such as repetitions/non-repetitions, and negative priming.

Because our work has been, and continues to be very much theory-driven a good deal of this report is devoted to a description of the DO'90 and DO'97 models. Summary descriptions of the empirical work appears following the models sections.

## II. THE DIMENSIONAL OVERLAP (DO) MODEL

The dimensional overlap model was originally formulated (Kornblum et al. 1990) to provide a unified theoretical framework for a broad family of stimulus-response and stimulus-stimulus compatibility tasks that, up to that point, had been treated as separate and unrelated phenomena. These tasks include the straightforward S-R compatibility tasks originally introduced by Fitts (Fitts & Deininger 1954, Fitts & Seeger, 1953), the so-called “Simon” task (Simon, 1969), the Stroop (1935) and Stroop-like tasks (Morton & Chambers, 1973), and others. The model had two parts: a representational part and a processing part. The representational component has changed very little since its inception, and forms the basis of the taxonomy of tasks in terms of which we view and partition our problem domain. The processing component has been modified, extended, and, most recently, expressed in a computational form (see Kornblum, et al., under review, and Stevens et al., 1996).

Because the taxonomy accommodates the many different kinds of tasks that generate the issues that we shall be addressing, we shall use the taxonomy as our conceptual frame of reference in the ensuing expositions and discussions.

## **II.A - Dimensional Overlap, 1990: Information Flow (DO-'90)**

At the core of the model is the idea that when a particular stimulus-response ensemble produces either high or low compatibility effects, it is because the stimulus and response *sets* in the ensemble are similar- i.e. they have some important characteristics in common. We have called this the *dimensional overlap (DO)* between stimulus and/or response sets. Dimensional overlap is defined as the perceptual, conceptual, or structural similarity that exists between stimulus sets, and/or stimulus and response sets, and may exist between the relevant stimulus and the response dimensions (called *relevant SR overlap*), between the irrelevant stimulus and the response dimensions (called *irrelevant SR overlap*), or between the relevant and the irrelevant stimulus dimensions (called *SS overlap*). Given any SR ensemble, DO may exist between none, two, or all three of these dimensions, thus giving rise to the eight different classes of potential S-R ensembles that comprise the model's taxonomy. These eight classes make up the taxonomy that we have been using to categorize the various compatibility tasks (see Kornblum & Lee, 1995).

In the next three sections I summarize the essential aspects of the DO-'90 model, preceded by a glossary of terms (II.A.1). This summary includes: the representational component (II.A.2); the taxonomy (II.A.3); and the processing component of the model (II.A.4).

### **II.A.1 - Glossary of terms**

Because we use terms, in the model and in all of our discussion, that are in common usage, and we give these terms more circumscribed meanings than they ordinarily have, our terminology may be a source of confusion when old meanings intrude on new ones. In order to reduce the possible ambiguities that this may lead to we present a brief glossary of some of the critical terms in our model. This glossary also serves as a summary of some of the pivotal concepts in the model.

1. Dimensional overlap: the degree to which a stimulus and a response set, or two or more aspects of a stimulus set, or a response set, are perceptually, structurally, or conceptually similar.
2. Stimulus or response set: a collection of individual stimuli or responses.
3. Stimulus or response element: an individual stimulus or response.

4. Stimulus-response (S-R) ensemble: the stimulus set together with the response set used in a particular task.

5. Stimulus-response (S-R) mapping: the instructional assignment of the stimulus elements onto the response elements in an S-R ensemble. When the relevant dimensions of an S-R ensemble overlap, the S-R mapping is either congruent or incongruent.

a) Congruent S-R mapping: the mapping of stimulus elements onto the response elements that they automatically activate.

b) Incongruent S-R mapping: any of the possible S-R mappings in an S-R ensemble, except for the congruent mapping.

6. Mapping effect: the difference in reaction time between the congruent and the incongruent mapping conditions of an S-R ensemble, where the incongruent mapping precludes the use of a rule, and requires a search for the identification of the correct response.

7. Dimensional relevance:

a) Relevant dimension: a dimension that the subject is instructed to attend to, and has a correlation of one with the correct response.

b) Irrelevant dimension: a dimension that the subject is instructed to ignore, and has a correlation of zero with the correct response.

8. Consistency/inconsistency: when an irrelevant stimulus dimension overlaps with either a response or another stimulus dimension, and the values on these dimensions match on a particular trial, they are called consistent. When they conflict, they are called inconsistent. For example, a stimulus consisting of the word "RED," when printed in red, is S-S consistent; when the word "RED" is printed in blue it is S-S inconsistent. Similarly, a color patch mapped onto a left or right key-press response, when presented on the same side as the response is S-R consistent and when presented on the opposite side of the response, is S-R inconsistent.

9. Consistency effects: Consistency effects are the equivalent of mapping effects when one or more of the overlapping dimensions is irrelevant.

a) S-R consistency effect: the difference in reaction time between S-R consistent and S-R inconsistent trials, or conditions.

b) S-S consistency effect: the difference in reaction time between S-S consistent and S-S inconsistent trials, or conditions.

10. Compatibility: This is not a technical term in the dimensional overlap model. However, it is a term that is widely employed in the literature to describe sets, mappings, dimensions, tasks, etc. We have listed below some of the more commonly used instances of this term with a translation of each instance in terms of the concepts of the model.

a) – of sets: "highly compatible sets" are those that are identified in the model as having a high degree of dimensional overlap; "incompatible sets" are more properly called "non-compatible" because here the term usually refers to sets with low, or no dimensional overlap.

b) – of mappings: "highly compatible mappings" are those identified in the model as congruent; "incompatible mappings" encompass what the model defines as "incongruent mappings" in addition to S-R mappings in non-overlapping S-R ensembles. "Compatible" and "incompatible mapping" are sometimes also used in the literature to refer to what in the model we call "S-R consistent" and "S-R inconsistent."

c) – of stimulus dimensions: "highly compatible stimulus dimensions" are those that the model identifies either as "overlapping," or as "S-S consistent"; "incompatible stimulus dimensions" include those that the model identifies as "non-overlapping" or as "S-S inconsistent."

## II.A.2 - The representational component

This component has remained largely unchanged since its original formulation. According to the model, stimulus response compatibility (SRC) effects are due in part to the *dimensional overlap* between the stimulus and the response *sets* in a task. We define *dimensional overlap* as the degree to which the *sets* of items are perceptually, structurally, or conceptually similar. Dimensional overlap is thus a property of the mental representations of sets. In formalizing this concept (see Kornblum et al., 1990) we postulate that the stimulus and response sets in S-R ensembles are each relational systems. That is, the stimulus and response sets each consist of a set of elements, together with a set of relations and operations that define the structure of these elements with respect to a dimension or attribute. If a mapping can be constructed between the stimulus and the response sets in an ensemble that preserves the relations and operations of both sets, then the mapping is said to be isomorphic, or homomorphic, and the ensemble meets the necessary - but not the sufficient - conditions for dimensional overlap. The greater the number of relations that are preserved by such a mapping, the greater the degree of dimensional overlap. A further determinant of dimensional overlap is the degree of similarity between the dimensions, attributes, and structural features of the two sets. Note that DO is a continuously varying and not a discrete quantity, even though it is used dichotomously in generating the taxonomy (see below).

Because DO is such a central concept in the model, we gave high priority, very early in this project, to the development of an empirical procedure for independently assessing the degree of DO in a task. The Oliver & Kornblum (1991) study represents an important step in that direction, and has greatly strengthened the central concept of dimensional overlap.

### II.A.3 - The taxonomy

The taxonomy is a logical outgrowth of the representational component of the model. Given that an S-R ensemble has a minimum of one relevant stimulus dimension, one irrelevant stimulus dimension, and one relevant response dimension, and that DO may occur between none, two, or all three of these dimensions, there are at least eight potential classes of S-R ensembles that could be used to construct tasks. These are briefly described next.

According to this taxonomy, an S-R ensemble in which the relevant and irrelevant stimulus dimensions do not overlap either with each other or with the response dimension, is a Type 1 ensemble. When only the relevant stimulus dimension overlaps with the response, and there are no other overlapping dimensions, it is a Type 2 ensemble. When only the irrelevant stimulus dimension overlaps with the response, and there are no other overlapping dimensions, it is a Type 3 ensemble ("Simon" task). When only the relevant and irrelevant stimulus dimensions overlap with each other, and there are no other overlapping dimensions, it is a Type 4 ensemble ("Stroop-like" stimuli). When the relevant and irrelevant stimulus dimensions do not overlap with each other, but do overlap with the response (which is necessarily two dimensional), it is a Type 5 ensemble. When the relevant stimulus dimension overlap with the response and not with one of the irrelevant dimensions (which necessarily cannot overlap with response), but one of the irrelevant stimulus dimensions does overlap with the response, it is a Type 6 ensemble. When one of the irrelevant stimulus dimensions overlaps with the relevant dimension, and another irrelevant stimulus dimension overlaps with the response, it is a Type 7 ensemble. And finally, when the same relevant and irrelevant stimulus dimensions overlap with each other as well as with the response, it is a Type 8 ensemble ("Stroop" task).

Illustrative examples of these various ensemble types are easily constructed. We start out with, what is probably, one of the best known and most complex ensembles and, by stripping away its properties one by one, generate the other ensembles in the taxonomy. Imagine an S-R ensemble in which the relevant stimulus dimension is color, the irrelevant stimulus dimension color words, and the response dimension color names. This is a Type 8 ensemble in the taxonomy (obviously a Stroop task). Imagine now an S-R ensemble with the same stimulus dimensions, color and color words, but one in which the response dimension has been changed from color names to digit names. Although the stimuli would still be called "Stroop-like", the task has clearly been changed. According to our taxonomy, this is a Type 4 ensemble. Imagine next, taking this Type 4 ensemble and changing the irrelevant stimulus dimension from color words to digits. The relevant stimulus dimension is still colors, the response dimension is still digit names, but the irrelevant stimulus dimension is now digits which no longer overlaps with the relevant stimulus dimension (colors), but with the response dimension (digit names). This is a Type 3



Ensemble Type	Overlapping Dimensions			Illustrative Stimulus/Response Sets			Representative Studies
	S-R Dimensions		S-S Dimensions	Illustrative Stimulus Sets		Illustrative Response Sets	
	Relevant (S <sub>1</sub> )	Irrelevant (S <sub>2</sub> )	(S <sub>1</sub> -S <sub>2</sub> )	Relevant (S <sub>1</sub> )	Irrelevant (S <sub>2</sub> )	Response (R)	
1	NO	NO	NO	Colors	Position (L/R)	Digit Names	Many choice RT tasks that have no dimensional overlap  Fitts & Seeger, 1953; Fitts & Deininger, 1954  Simon & Small, 1969; Wallace, 1971  Keele, 1972; Kahneman & Henick, 1981; Ericksen & Ericksen, 1974  Hedge & Marsh, 1975  (None)  Stoffels & van der Molen, 1988; Kornblum, 1994  Stroop, 1935; Simon & Rudell, 1967
2	YES	NO	NO	Digits	Colors	Digit Names	
3	NO	YES	NO	Colors	Digits	Digit Names	
4	NO	NO	YES	Colors	Color Words	Digit Names	
5	YES	YES	NO	Colors	Position (L/R)	Key Presses (L/R) on Colored Keys	
6	YES	NO	YES	Position (L/R)	Colors/Color Words	Key Presses (L/R)	
7	NO	YES	YES	Colors	Color Words/Position (L/R)	Key Press (L/R)	
8	YES	YES	YES	Colors	Color Words	Color Names	

Table 1. A taxonomy of stimulus-response ensembles according to the dimensional overlap model (Kornblum, 1992; Kornblum et al., 1990).

ensemble, of which the spatial, and probably best known, version is the so-called "Simon task" (Simon, 1990).

Now, if one were to retain colors as the relevant stimulus dimension, and color words as the irrelevant stimulus dimension (like in Type 4) and present these compound stimuli to the left and right of a fixation point - *with location irrelevant* - and require left/right key press responses, this would be a Type 7 ensemble in which Type 3 and Type 4 are combined. Keeping color as the relevant stimulus dimension and position as the irrelevant stimulus dimensions, and dropping color word as an irrelevant stimulus dimension, but adding color to the keys as the relevant response dimension produces a Type 5 ensemble. To construct a Type 2 ensemble let us return to the Type 3 ensemble, and simply reverse the relevant and irrelevant stimulus dimensions in that ensemble. That is, the stimuli still consist of colored digits and the responses are still digit names, but instead of having colors be relevant and digits irrelevant, digits are now made relevant and colors irrelevant. This is a Type 2 ensemble and describes the standard SRC tasks. Finally, an S-R ensemble in which colors are relevant, shapes (of the color patch) irrelevant, and digit names the response, would be a Type 1 ensemble. When properly designed (see Kornblum & Lee, 1995), Type 1 ensembles may serve as neutral baselines to evaluate the effects of dimensional overlap in other ensembles.

#### II.A.4 - The processing component

This component has undergone a number of changes since its inception. First, it has gone from, what was relatively speaking, an information-flow model (or boxology) to a full fledged computational model (DO-'97); second, the new version of the model now includes explicit dynamic properties that it was previously lacking; and third, the new model accounts not only for within, but for between trial effects. I recapitulate the properties of the earlier version (DO-'90) first, simply because it remains the conceptual foundation of the model; I then summarize some of the properties of the more recent computational version (DO-'97) of the model in section II.C

The original processing model (Kornblum et al, 1990; Kornblum & Lee, 1995) includes two modules with stage-like characteristics (cf. Sternberg, 1969) separated by a cut-point (cf. Schweickert, Fisher & Goldstein, 1991) that makes their effects additive (this additivity feature has been modified - see below): the stimulus-identification and the response-production modules.

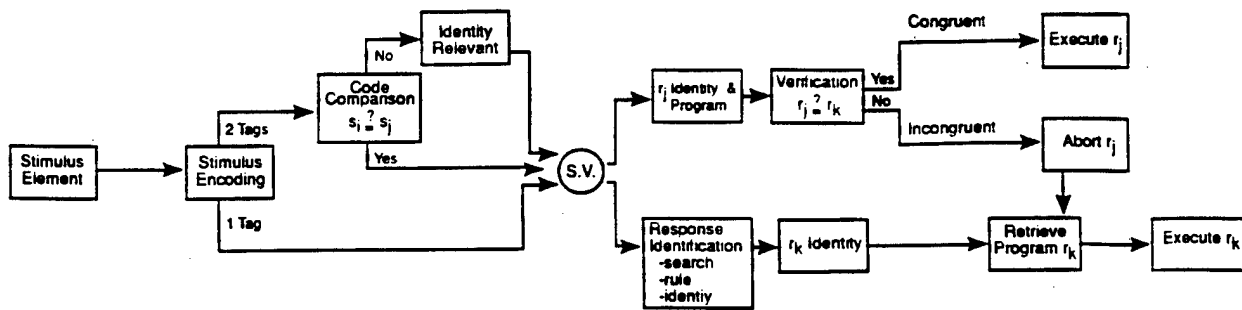


Figure 1. The dimensional overlap processing model (DO-'90). The stimulus vector (S.V.) marks the cutpoint in the network. To the left of the cutpoint is the stimulus identification stage; to the right is the response production stage.  $s_i$  = a stimulus attribute that overlaps with another stimulus attribute;  $s_j$  = a stimulus attribute that overlaps with a response attribute;  $r_j$  = an automatically activated response;  $r_k$  = the correct response.

### Stimulus identification

The model postulates that if the relevant and irrelevant *stimulus* dimensions overlap (S-S overlap, e.g. Type 4 ensemble) then the presentation of a stimulus element automatically activates two stimulus-identification codes as potential relevant stimuli. If the two codes, or features, are the *same*, then it matters little which is tagged as relevant. If the two codes differ, then one of them is tagged as relevant and passed along, with all the other stimulus features. Stimulus information is passed from the stimulus module to the response module in a *stimulus vector* that includes all the stimulus attributes, or features, that were encoded by the stimulus identification module with the relevant attribute being *tagged* as relevant.

### Response production

The response production module has two paths: *automatic activation* and *response identification*. If the stimulus and response sets have dimensions that overlap (either relevant or irrelevant S-R overlap; e.g. Types 2 or 3 ensemble), the presentation of an element from the stimulus set automatically activates its corresponding element in the response set. This process is similar to that triggered by an explicit prime or precue (see Posner & Snyder, 1975), and is represented by the upper branch of the response production module in Figure 1. Before this response can be executed, however, the *correct* response (i.e. the one specified by the mapping instructions) must be identified, and this is done in the lower branch (Figure 1).

When there is *no S-R overlap* (e.g., ensemble Type 1), there is *no automatic response activation*, and response identification proceeds by search, or table look up, which by

assumption, is the longest and most time consuming of the identification procedures. When there is S-R overlap (e.g., ensemble Type 2), in addition to the automatic response activation process, the overlap introduces the potential of using a *rule* in order to get from the stimulus to the correct response. The simplest, and fastest, rule is the identity rule as, for example in the case where the stimulus set consists of the digits 1, 2, 3, 4 and the response set consists of the digit names ONE, TWO, THREE, FOUR, and the mapping instructions assign the stimulus digits to their own names as responses. There are other rules, of course, that are more complex and, by assumption, more time consuming. For example, if the stimulus set is viewed as a loop, then the mapping instructions could be given as "correct response = stimulus plus two," which would define THREE, FOUR, ONE and TWO as the correct responses for the stimuli 1, 2, 3 and 4, respectively. Even though the use of a rule requires the presence of S-R overlap (see Kornblum et al., 1990, p. 260; Fn. 7) the existence of such overlap does not necessarily force the use of a rule, or exclude the use of a search procedure. Thus, the duration of the response identification process may, but need not be, affected by the presence of S-R overlap.

If, following response identification, the automatically activated and the correct responses do not differ, then the response so identified is executed without further ado. But if the two responses differ, then the automatically activated response is aborted, the program for the correct response retrieved, and the response is then executed. The prolongation of RT with incongruent mapping is thus attributable to two sources: response identification, and the abort procedure that follows from the automatic activation of the congruent, but erroneous response.

## II.B - Other theories

Before going on to the computational version of the model (DO-'97), we summarize how some of the earlier theories that have been proposed for different aspects of SRC are either consistent with, sometime follow quite naturally as logical consequences from, or are addressed by, the DO model.

Fitts viewed SRC effects as "...resulting from hypothetical information transformation processes (encoding and/or decoding) that intervene between receptor and effector activity...[such that]...The rate of processing information is assumed to be maximum when these processes are at a minimum." (Fitts and Deininger, 1954, p. 483). It is easy to read this statement as a broad stroke description of the DO model, including its stimulus processing stage, and its response production stage with the response identification process within the latter. [The basic information-theoretic idea implicit in Fitts' account was later elaborated as the "coding hypothesis" (e.g. Wallace, 1971; Nicoletti & Umiltà, 1984, 1985), and the "salient feature principle (Proctor & Reeve, 1985)]. When he wrote on SRC, Fitts had in mind only Type 2 tasks even though some of the later elaborations dealt with Type 3 tasks. It was Simon who,

when he found that *irrelevant* spatial stimulus locations (left/right) produced a significant S-R consistency effect in two-choice keypressing tasks (DO Type 3) proposed that this finding might be accounted for by "...postulating an innate tendency in humans to respond toward the source of stimulation." (Simon, Craft & Webster, 1973, p. 177). Simon had originally proposed this to account for spatial compatibility effects that he had obtained with a Type 2 task (Simon 1969). The basic principle being invoked by Simon is reflected in the DO model's much more general principle: *the automatic response activation hypothesis*, for which predictions to domains other than spatial positions have been experimentally corroborated (e.g. Kornblum & Lee, 1994). When dimensional overlap starts no longer being restricted to stimulus and response dimensions (whether relevant or irrelevant) and includes S-S overlap - like in Type 4, and especially Type 8 tasks - then theories may be seen as splitting between *early* and *late* selection accounts. This split maps easily into explanations based either on the stimulus processing or on the response production stage of the DO model. There is a vast literature on Type 8 tasks that has recently been reviewed (McLeod, 1991) so that there is no need to do so here.

When first reported by Hedge & Marsh (1975), performance with Type 5 tasks seemed to challenge both Simon's notion of "...an innate tendency to responses toward the source of stimulation...", and the DO model's automatic response activation hypothesis. In essence, what Hedge & Marsh found was that under certain conditions the RT for S-R consistent trials was slower than for S-R inconsistent trials. At the time they formulated the *logical recoding hypothesis* which stated that:

"For a given logical recoding (identity or reversal) of the relevant attribute ... responding was faster for trials in which the recoding of the irrelevant attribute ... was of the same logical type as that of the relevant attribute, than for trials in which the logical recoding of the irrelevant attribute was opposite in type." (Hedge & Marsh, p. 435).

This hypothesis was later incorporated by DeJong et al. (1994) in their "dual-process model" for Type 5. However, our experimental results (see section III) strongly suggest that neither the original (Hedge & Marsh, 1975) nor the updated (DeJong et al. 1994) version of the logical recoding hypothesis appear to be sustainable. The DO-'97 model, on the other hand, appears to have captured important aspects of performance with this Type of task.

In addition to these specific theories that deal with particular task Types, there is the general issue of whether information processing in the processing structure is discrete or continuous. This has been a bone of contention both inside and outside the SRC literature (for a review, see Miller, 1988) for a number of years now. Starting with Eriksen's (Eriksen & Schultz, 1979) account of the results that he obtained with his "flanker task", up through Hommel's formulation of his temporal overlap model (Hommel, 1993), there has been a steady stream of arguments supporting the continuous vs. the discrete position. This issue is related to, but very

different from, the question of whether automaticity is an all or none phenomenon, or a gradient, as proposed, for example, by Kahneman & Chajczyk (1983) (also see Miller 1988). On the latter question, the DO model argues that dimensional overlap, hence automaticity, varies continuously rather than discretely (see also Cohen et al., 1990). The former question is addressed in DO-'97, where we show that the discrete position is not only tenable, but is supported by both the behavioral data, and simulations from the model (see section II.C.2, and III.1).

Thus, many of the theoretical issues that different investigators have raised by focusing on different aspects of the SRC story are addressed by the DO model - which seems only proper if our claim to be developing a *general* model is to have any validity.

### **II.C - Dimensional Overlap, 1997: The computational model (DO-'97).**

We have chosen a PDP (Parallel Distributed Processing) architecture to develop the computational version of the model. The architecture is divided into two layers, an input layer and an output layer. Processing in the output layer does not begin until the output of a unit in the stimulus layer reaches this threshold. As a result, processing in these layers can be understood in terms of the separate, sequential stages as described in DO-'90: the stimulus identification stage (input layer) and the response selection stage (output layer). However, because this model includes temporal dynamic properties, the stages in the computational version of the model are not independent, and do not give rise to additive effects in the AFM sense (see section II.C.2)

Within each layer, processing takes place within interconnected modules. Each module consists of a set of elementary processing units (McClelland 1993; Rumelhart, Hinton and McClelland, 1986). As with other PDP models that deal with S-S and S-R compatibility effects (e.g. Cohen & Huston, 1994; Cohen, Dunbar, and McClelland, 1990; Cohen, Servan-Schreiber, and McClelland, 1992; Phaf, van der Heijden, and Hudson, 1990; Zhang, 1994; and Zorzi & Umiltà, 1995), these modules represent dimensions -- or mutually exclusive classes of features -- of either stimulus properties (when the modules are in the input layer) or response properties (when the modules are in the output layer). The activation of a unit within a module, therefore, represents the activation of a feature (either stimulus or response) along that dimension.

#### **II.C.1 - Architecture and connectivity**

The general model is shown in Figure 2, showing (for illustrative purposes) a configuration with one relevant and one irrelevant stimulus module, and one response module.

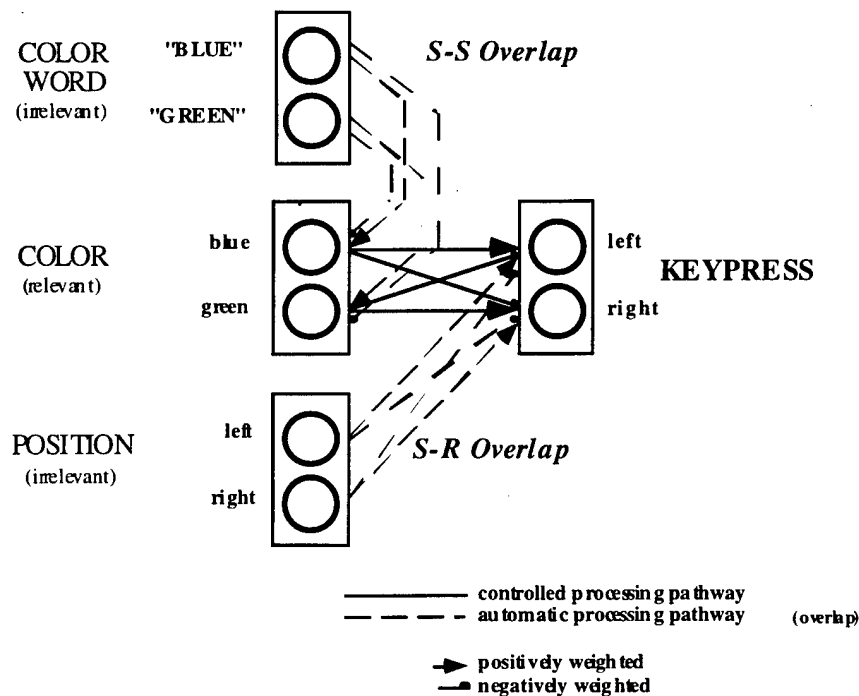


Figure 2. Architecture of the model (see text for explanations).

Connections between modules are of two types: automatic and controlled. Automatic processing lines connect modules that represent dimensions that overlap. The strength of these connections ( $\delta$ ) is proportional to the degree of DO between them. Thus, when the relevant and irrelevant stimulus dimensions overlap (i.e. when there is S-S overlap, as for example in Types 4, 6, 7 and 8) there are automatic connections between the two stimulus modules in the input layer. When there is overlap between the irrelevant stimulus and the response (i.e. when there is irrelevant S-R overlap, as for example in Types 3, 5, 7 and 8), there are automatic connections between the irrelevant *stimulus* module in the input layer and the *response* module. Finally, when there is overlap between the *relevant* stimulus and the *response* (i.e. when there is relevant S-R overlap, as for example in Types 2, 5, 6 and 8), there are automatic connections between the relevant stimulus module in the input layer and the response module.

In addition to the automatic lines, there is a set of controlled processing lines. These controlled lines, rather than being specified by the overlap (DO) between dimensions, are specified by the demands of the experimental task itself; thus, they connect the relevant stimulus module with the response module. (Indeed, the *relevant* stimulus module could be defined as that module in the input layer that is connected to a response module by a *controlled* line - see also the GLOSSARY section II.A.1). Furthermore, instead of being continuously weighted, like the

automatic processing lines, the controlled lines transmit binary signals of either “on” or “off”, depending on whether the stimulus has been identified or not, in order to initiate the correct response. In this way, the controlled process represents a *decision* process: Once enough evidence has accumulated in the input layer (so that the input activation has passed a threshold), a response is initiated based on the stimulus that has gained sufficient evidence. This process, which gives our model its stage-like behavior, is elaborated more fully in the next section.

Following models proposed by Cohen et al. (1992), and Phaf, van der Heijden, and Hudson (1990), both automatic and controlled information processing pathways consist of positive (excitatory) connections between the “corresponding” units of each module, and negative (inhibitory) connections between the “non-corresponding” units of each module. Thus, when the *irrelevant* stimulus dimension is stimulus location (L/R), and the *relevant* response dimension is response location (L/R), *excitatory* automatic lines connect the “left” stimulus unit with the “left” response unit, and the “right” stimulus unit with the “right” response unit. Furthermore, *inhibitory* automatic lines also connect the “left” stimulus unit with the “right” response unit, and the “right” stimulus unit with the “left” response unit.

This pattern of connectivity ultimately enables the model to account for both *facilitation* effects (via the excitatory effect of co-activation of compatible features) and *interference* effects (via the inhibitory effect of co-activation of incompatible features). Some models have accounted for interference effects by having inhibitory connections *between* units of the same module, thus forcing units within each module to compete for activation (e.g. Cohen, Servan-Schreiber, and McClelland, 1992; Grossberg, 1976; McClelland, 1993; McClelland and Rumelhart, 1981; Zorzi and Umiltà, 1995); other models have incorporated both *intra-* and *inter-module* inhibition (e.g. Phaf, van der Heijden, and Hudson, 1990; Zhang, 1994). Our decision to have inhibitory lines *between* non-corresponding units of different modules, rather than among units *within* each module, is motivated by sheer model simplicity. Little theoretical or empirical evidence exists to motivate a preference for one over the other (e.g. see Mordkoff, 1995), and no solid convention appears to have been agreed upon in the literature.

This architecture and pattern of connectivity specify the pathways through which information flows in our model. When a two-dimensional stimulus is presented, it activates a feature in the *relevant* stimulus module, and a feature in the *irrelevant* stimulus module. The information in these modules is then processed according to the model’s connectivity, until a response is produced. In order to get a clearer picture of how this information flow takes place, we discuss next how the units themselves process information.



### II.C.1.a - Activation and Information Flow

In almost all PDP models designed to simulate RT phenomena (e.g. Cohen, Dunbar and McClelland, 1990; McClelland, 1992; Zhang, 1994; Zorzi and Umiltà, 1995), the individual processing units are “feature detectors” in which activation gradually accumulates over time. With a few notable exceptions (e.g. Phaf, van der Heijden, and Hudson, 1990), this is usually accomplished by using an activation function similar to that first used by McClelland (1979) in his cascade model. The activation function that we use is identical to those.

Thus, at time  $t$ , units take as their net input the weighted sum of the outputs of units connected to it, so

$$\text{net}_j(t) = \sum o_i(t)w_{ij} \quad [1]$$

where  $o_i(t)$  is the output at time  $t$  of each unit from which unit  $j$  receives input, and  $w_{ij}$  is the weight (or strength) of the connection from unit  $i$  to unit  $j$ . The activation of a unit is simply a running average of its net input over time, so

$$a_j(t) = \alpha \text{net}_j(t) + (1 - \alpha) a_j(t-1) \quad [2]$$

where  $\text{net}_j(t)$  is the net input to unit  $j$  at time  $t$  and  $\alpha$  is a rate constant. This time-averaging function establishes the time-course of processing in the model. One feature of this function is that when the input to the unit is fixed, the activation will gradually climb through time, and will asymptotically approach a value equal to the input (McClelland 1979).

In order to produce the output of the unit, the activation is passed through a logistic function that introduces nonlinearity into the model, thus giving the network a variety of desirable characteristics (see Cohen, Dunbar and McClelland, 1990 for discussion). The output function is calculated by

$$o_j(t) = \frac{1}{1 + e^{\kappa(-a(t))}} \quad [3]$$

where  $a(t)$  is the activation of the node for which the output is being calculated at time  $t$ , and  $\kappa$  controls the degree of nonlinearity of the function.

As described earlier, our model also includes one feature that does not appear in previous models of S-S and S-R compatibility: There are *thresholds* at the output of *both* the input and the output layers, rather than at the output layer only, as is generally the case (e.g. Cohen, Dunbar, and McClelland 1990; McClelland 1992; Zhang 1994;). Furthermore, until some unit in the input

layer reaches the *stimulus threshold* (the threshold for the output of the input layer), the activation of the units in the response module are *clamped to zero* (see Hinton and Sejnowski, 1986, 289-290 on this terminology), and no processing is allowed to take place in the response module. *This unique feature gives our network the characteristics that make it similar to serial stage models of reaction time.* For example, in our model any reaction time can be decomposed into the duration of a *stimulus processing stage*--the time from the onset of the stimulus to the time when activation in one of the units in the input layer reaches threshold, and the duration of a *response production stage* -- the time from the beginning of response processing (i.e. when the stimulus threshold is reached), to the time when activation in one of the units in the response module reaches threshold. These two quantities are then *added* together to produce the overall reaction time; in fact, this is precisely how our simulations work.

Furthermore, when *activation* in one of the units in a layer (either stimulus or response) reaches threshold, processing in that stage is assumed to be completed, so *input* to the relevant units (either input to the relevant stimulus unit, when the stimulus threshold is reached, or input via the controlled line to the relevant response unit, when the response threshold is reached) is *turned off* (given a value of zero). However, because the activation function is a time-averaging function, *activation will only gradually decay* back to zero after the threshold is reached. This gradual decay in both the activated relevant stimulus unit and the response units allow the model to account for *relevant S-R* (e.g. Type 2) compatibility effects, as well as *inter-trial* effects.

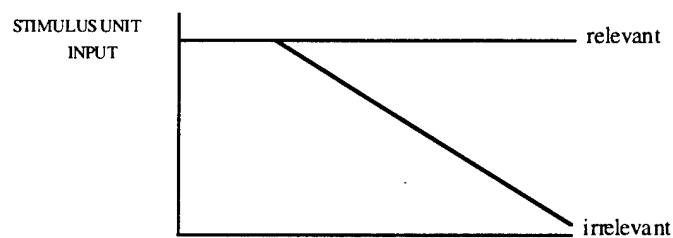
Conceptually, then, the flow of information can be described as follows: when the stimulus is first presented, activation begins to accumulate in units of the input layer that correspond to features in the stimulus. To the degree that there is S-S overlap, the activation of different units, corresponding to different stimulus features, may interact with one another -- producing either facilitation or interference. When a particular unit's activation level reaches the stimulus threshold, a *decision* may be said to have been made about the specific stimulus that will form the basis of the response. At this point, signals from that stimulus unit are sent via the controlled lines to the response units, and automatic activation from units in the stimulus layer is also permitted to influence units in the response layer via the automatic S-R processing lines. Activation in the relevant stimulus unit begins to decay back to zero, while signals sent through the controlled lines lead to an accumulation of activation in the response units. Because the controlled lines also consist of both positive and negative connections, activation in the correct response will increase, while activation in the incorrect responses will decrease (below zero). With S-R overlap, activation of either the relevant stimulus unit (in the case of relevant S-R overlap) or the irrelevant stimulus unit (in the case of irrelevant S-R overlap) leads to the automatic activation of the corresponding response unit, which interacts with the accumulation of activation in the response units due to the controlled lines. This interaction is either facilitative

(in the case of S-R consistency), or interfering (in the case of S-R inconsistency), and continues until the activation level in a response unit reaches the response threshold, and a response (presumably the correct response) is chosen. Once this threshold is met, activation in the response units is also allowed to decay back to zero.

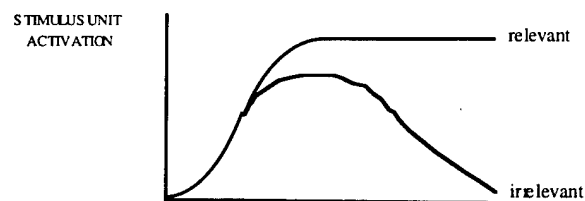
This competitive activation process cum threshold in the response layer corresponds roughly to a combined verification and abort stage, as postulated in the original DO-'90 model (Kornblum et al. 1990), described above. In order to understand the model's dynamics we must now examine the time course of irrelevant stimulus activation which is a critical aspect of the model.

### II.C.1.b - Irrelevant stimulus activation

We postulate that the inputs to both the relevant and the irrelevant stimulus units start at some value (set at 1 for the simulations). The input to the relevant unit remains at that value, while input to the irrelevant unit decays at a fixed rate ( $\rho$ ) beginning a brief interval ( $\tau$ ) after its onset (Figure 3A).



A.



B.

Figure 3. A: Input to the relevant and the irrelevant stimulus units sketched as a function of time; B: Activation functions in the relevant and the irrelevant stimulus units, sketched as a function of time.

In accordance with Equation 2, these inputs will cause the activation levels in both the relevant and the irrelevant stimulus units to increase - at first. However, as the *input* to the *irrelevant* stimulus unit starts to decay the *activation* level in that unit will level off and start to decrease, while the *activation* level of the *relevant* unit will continue to increase until it reaches threshold at time *t* (see Figure 3B). As a result, irrelevant activation follows a non-monotone, inverted-U shaped curve.

Automatic activation of the irrelevant stimulus affects performance by altering the *rate* at which activation builds up (see Equation 2) for the *relevant stimulus* (in the case of S-S overlap), and for the *response* (in the case of S-R overlap). Hence, S-S and S-R overlap *alter the time* required for activation in either the relevant stimulus, or the response units to reach their respective thresholds (see Figure 4). In particular, when the

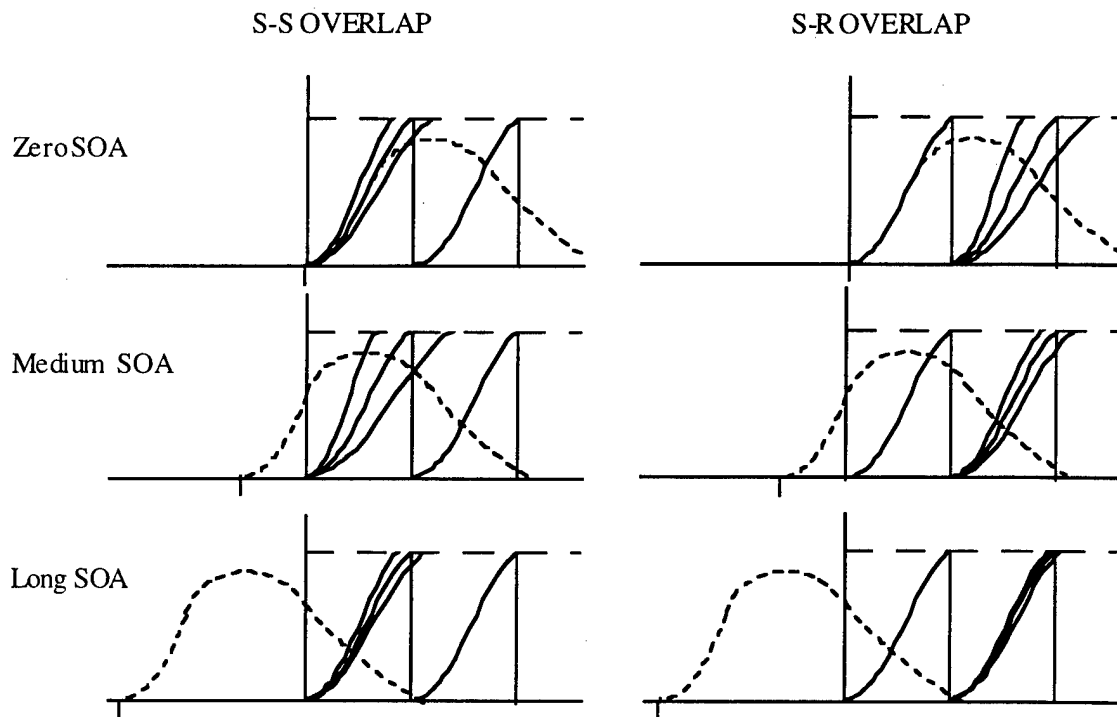


Figure 4. The effects of SOA on model dynamics. On the left are sketched the effects of an irrelevant stimulus with S-S overlap; on the right are the effects of an irrelevant stimulus with S-R overlap. SOA increases from top to bottom. The horizontal long-dashed lines represent thresholds for the stimulus (left) and response (right) stages. The short-dashed, inverted U-shaped line represents the activation function of the irrelevant stimulus, and shifts to the left as SOA increases; tick marks on the horizontal axis indicate the onset of the irrelevant stimulus. The "ordinate" represents the strength of activation, and marks the point in time when the relevant stimulus is presented. The other two vertical lines on each graph mark the point in time when the relevant stimulus (the first line) and the response (the second line) activation levels have reached threshold, in the absence of any enhancement or degradation by the irrelevant stimulus - i.e. neutral. The two lines straddling the neutral activation functions represent the enhanced (accelerated in the case of consistent relationships), and degraded (slowed in the case of inconsistent relationships) activation functions. (see text for further explanations).

*irrelevant* stimulus is *consistent* either with the relevant stimulus (S-S consistent) or with the response (S-R consistent), activation in the appropriate unit grows at a *faster* than normal rate, hence reaches threshold sooner; when the irrelevant stimulus is *inconsistent* (S-S or S-R inconsistent), activation grows at a *slower* than normal rate, thus reaching threshold later. Furthermore, because, in the case of S-R overlap, the irrelevant stimulus cannot exert its influence on the response unit until *after* the stimulus processing stage has been completed (recall that the response units are clamped to zero until after completion of stimulus processing), this influence will involve a later point on the activation curve of the irrelevant stimulus than in the case of S-S overlap. This has important consequences for the time-course of S-S and S-R consistency effects.

#### II.C.1.c - Processing variability

The final specification of the model is the introduction of processing variability. Human performance is inherently variable. Reaction time data thus come as distributions. In previous models, this variability has been simulated by adding *Gaussian* noise to the net input of each unit on each trial (cf. Cohen, Dunbar and McClelland, 1990). However, reaction time distributions are generally skewed (e.g. Luce, 1986), and moreover, many of the values in which variability might occur in such models (e.g. threshold values, strength of DO) have theoretical lower limits (e.g. zero), so that using normally distributed noise isn't theoretically sound. In order to capture the skewed nature of this variability, as well as to be able to set theoretical lower limits on the values in which noise is introduced, we used *gamma-distributed* noise (see Luce 1988). Noise of this type is introduced at the *inputs* of units at each stage (layer), as well as at the *end* of processing in order to represent execution variability. In order to simulate individual differences between subjects, we also introduce noise with these properties to the threshold ( $\theta$ ), DO ( $\delta$ ), and time-delay ( $\tau$ ) parameter values. This integrated approach to the variability issue has enabled us to simulate the actual RT distributions fairly closely, as is indicated by our simulated distributional plots (see III.1).

#### II.C.1.d - Architecture Summary

1. Presentation of a *relevant* stimulus feature generates a *constant input* of 1 to the corresponding stimulus unit; presentation of an *irrelevant* stimulus feature generates an *input* to the corresponding stimulus unit that is *initially* 1. However, after some period of time  $\tau$ , this irrelevant input decreases linearly with a slope  $p$ . These inputs result in two differently shaped *activation functions*: the activation function in the *relevant* stimulus unit which resembles a logistic function, and that in the *irrelevant* stimulus unit which has an inverted U-shape.

2. Activation in the *input* modules rises from the onset of the stimulus until the output of a unit reaches the stimulus threshold, at which point the relevant input is turned off and activation decays. This is considered the *stimulus processing stage*. During this period of time the response module remains inactive. However, if there is *S-S overlap* then *the two stimulus modules can interact* through automatic processing lines

3. Once the stimulus threshold is met, the controlled line begins sending an input value of 1 to the response unit designated by the task, and an *inhibitory* signal to the incorrect responses (leading to below-zero inhibition), while activation in the stimulus modules (relevant or irrelevant, depending on the type of DO present) is allowed to start acting on the response module via S-R automatic processing lines (if there is S-R overlap). Activation in the response module accumulates until one of the units reaches the response threshold. This is considered the *response processing stage*

4. Processing connections between modules are *excitatory* between corresponding, or consistent units, and *inhibitory* between non-corresponding, or inconsistent units. The weight of automatic lines ( $\delta$ ) is proportional to the degree of DO between the dimensions represented by the modules in question. Controlled lines are given a weight of 1, in order to simulate a “ON/OFF” decision process. Any asymmetry between the net inhibition caused by co-activation of non-corresponding units and the net facilitation caused by co-activation of corresponding units can be taken as a parameter  $\phi$ : the ratio of inhibition / excitation.

5. Reaction time is the total number of timesteps between the onset of the stimulus and the point when a unit in the response module reaches the response threshold. *Variability* in reaction time is introduced by adding *gamma distributed noise* to the *net input* of each unit, and to the *output* of the response layer.

6. The net input to a unit in each module can, therefore, be specified. For the *relevant stimulus unit*, when relevant and irrelevant stimuli are *consistent*,

$$\text{net}_r(t) = 1 + \delta o_i(t) \quad [4a]$$

and when they are *inconsistent*,

$$\text{net}_r(t) = 1 - \delta \phi o_i(t) \quad [4b]$$

where  $\delta$  is the degree of S-S DO, where  $\phi$  is the ratio of DO inhibition (due to inconsistency) to excitation (due to consistency), and  $o_i(t)$  is the output of the irrelevant stimulus unit.

For the *irrelevant stimulus unit*, when relevant and irrelevant stimuli are *consistent*:

$$\text{net}_i(t) = (1 - \nu\rho) + \delta o_r(t) \quad [5a]$$

and when they are *inconsistent*,

$$\text{net}_i(t) = (1 - \nu\rho) - \delta \phi o_r(t) \quad [5b]$$

where  $\nu$  is equal to zero until time  $(t)$  reaches the “*attentional delay interval*” (described as  $\tau$  above), and it equal to  $(t - \tau)$  after that, and where  $\rho$  is equal to the slope of the decrease in input to the irrelevant unit.  $o_r(t)$  is the output from the relevant stimulus unit.

For the *response unit*, when irrelevant stimulus and response are *consistent*:

$$\text{net}_r(t) = 1 + \phi o_i(t) \quad [6a]$$

and when they are *inconsistent*,

$$\text{net}_r(t) = 1 - \delta \phi o_i(t) \quad [6b]$$

where the activation begins at zero from when the stimulus threshold is met (as opposed to the onset of the stimulus itself), whereas the output of the irrelevant stimulus unit,  $o_i(t)$ , is the same output that has been calculated since the initial onset of the stimulus.

### II.C.2 - Stage interdependence

The activation in the irrelevant stimulus module only becomes critical when there is some relationship (DO) between the irrelevant stimulus features and some aspect of the task--either stimulus or response. If there is no relationship (no DO), then the irrelevant stimulus activation has no effect. If the irrelevant feature is related to the stimulus (S-S overlap), then it affects the *rate* at which the activation function of the relevant stimulus unit reaches threshold: speeding it up if it is consistent, slowing it down if it is inconsistent. If it is related to the response (S-R overlap) then it will have the same effect in the response unit: increasing the rate at which the response activation reaches threshold when it is consistent, and decreasing this rate when it is inconsistent. If it is related to both, then, of course, it will have the appropriate effects in the appropriate units of each layer (stage).

What is critically important to note, however, is that *the magnitude of the influence of the irrelevant stimulus is directly determined by its level of activation*. For example, the higher the activation level of the irrelevant stimulus at the onset of the response stage, the greater the effect of irrelevant S-R DO. Because S-S overlap changes the *duration* of the stimulus-processing stage,

and because the level of activation of the irrelevant stimulus is continuously changing through time (according to an inverted U-shape, discussed above), S-S overlap directly determines the value that the irrelevant stimulus activation curve has at the onset of the response-selection stage. In this way, the duration of the response-selection stage depends on the duration of the stimulus-processing stage. This dependency arises, in effect, *because* the two stages are serially ordered: changes in the duration of the first stage influence the time at which the second stage is allowed to begin, while the duration of the second stage depends upon when it begins. Empirically, this is observed as an S-S x S-R interaction.

During the next phase of this project a considerable effort will be devoted toward obtaining a better understanding of how the levels of activation in the relevant and the irrelevant stimulus and response units interact in producing *intra*- as well as *inter*-trial effects such as repetition and non-repetitions, negative priming, and task switching.

### **III. - Empirical studies**

Here, instead of reporting *all* the work that we have done on SRC (see section VI. PUBLICATIONS), we summarize the results of a few selected studies from our laboratory that seem to address central issues in the DO model, to have advanced the model in significant ways, and to be raising new issues that are being addressed in our current work.

#### **III.1 - The differential consistency effects of S-S and S-R overlap, and the interdependence of the stimulus and response stages.**

The way irrelevant stimuli interact with either the relevant stimuli, or the responses has been a problem of central concern to investigators of the Stroop and Simon tasks, as well as to others with broader interests like selective attention. According to the DO perspective, irrelevant stimuli overlap either with the response (S-R overlap, of which Type 3 is the simplest instance), with the relevant stimulus (S-S overlap, of which Type 4 is the simplest instance), with both (Type 7 or 8), or with neither (Type 1). That is, S-S and S-R overlap are each based on different aspects of the S-R ensemble and, because of the processing postulates of the DO model, have different processing consequences. In particular, S-S consistency effects have their origins in the stimulus processing stage while S-R consistency effects have their origins in the response production stage. Accordingly, because of the temporal overlap between the irrelevant stimulus activation function and the seriality of the two processing stages (see sections II.C.1.b and II.C.2 above, and Kornblum et al. submitted), they are each predicted to have different time courses.



We tested this proposition in a series of experiments in which we used two-choice tasks with Types 3, 4 and 7 ensembles and, in order to examine the time course of the S-S and S-R consistency effects, we introduced a delay (SOA) between the presentation of the irrelevant and the relevant stimuli. In the first experiment (Kornblum, 1994) we used SOAs of 0 and 200 ms and found that with a zero delay, the S-R consistency effect was about 40 ms, and with a 200 ms delay it had dropped to 30 ms. In contrast, the S-S consistency effect was non-existent (5 ms non significant) at zero delay, but had grown to about 50 ms with SOAs of 200 ms.

Further experiments using a wider range of SOAs (0 to 800 ms) confirmed these initial observations and give us to have a fairly good idea of the time course for these two consistency effects. The *S-S consistency effect* appears to have an inverted-U shape with a peak at about 200 ms, while the *S-R consistency effect* appears to increase very rapidly, peak at about 50 ms and then decrease. These two trends are illustrated on Figures 7 and 9 and are also stimulated by DO-'97 (see Figures 8,10). These trends are confirmed in greater detail by the distributional analyses of the data, illustrated in Figures 11 and 13, which greatly strengthens the model's assertion that these two effects reflect the action of two *different* processes. Figures 12 and 14 show DO-'97 simulations of these distributional plots.

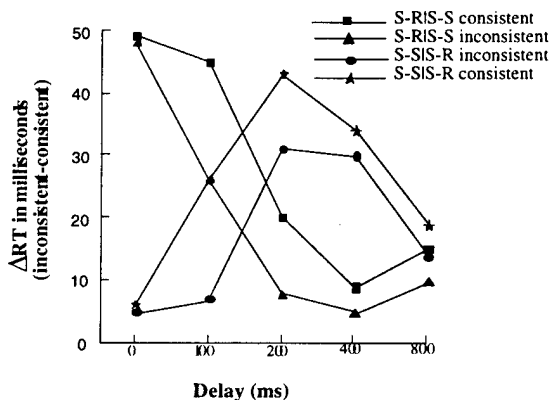


Figure 7. Mean S-S and S-R consistency effects for the four combinations of S-S and S-R consistency conditions in Experiment 2, plotted as a function of delay (SOA = 0-800), on a log scale.

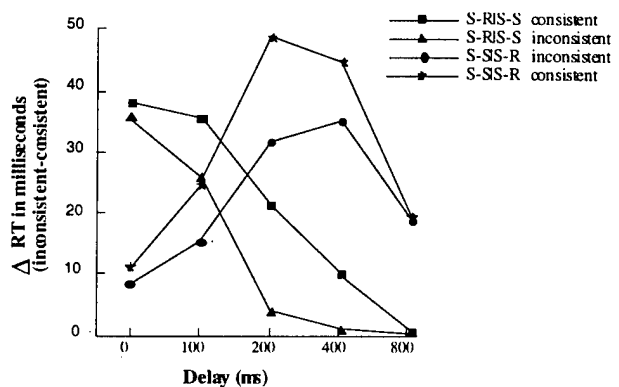


Figure 8. Simulated consistency effects for Experiment 2 (SOA = 0-800 ms).

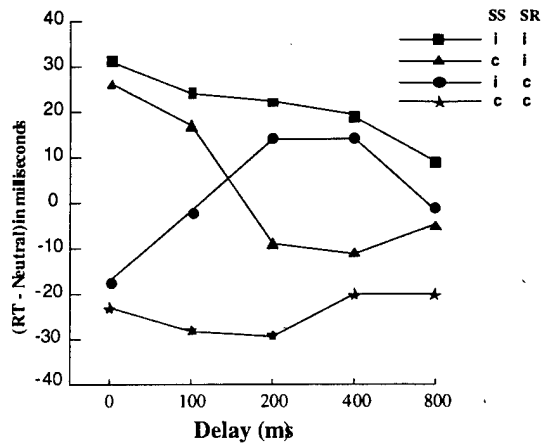


Figure 9. Mean RT differences (RT-neutral) for the four experimental conditions in Experiment 2, plotted as a function of delay (SOA = 0-800), on a log scale.

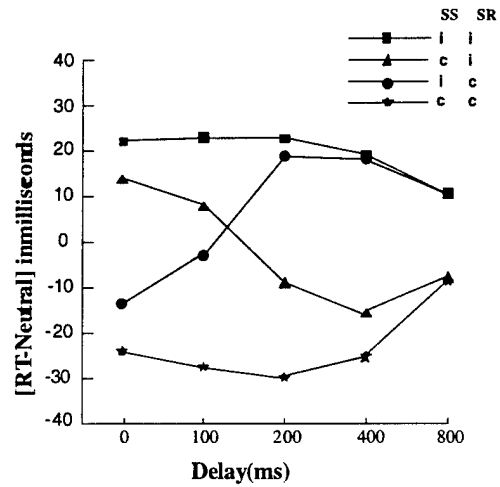


Figure 10. Simulated RT for Experiment 2 (SOA = 0-800 ms).

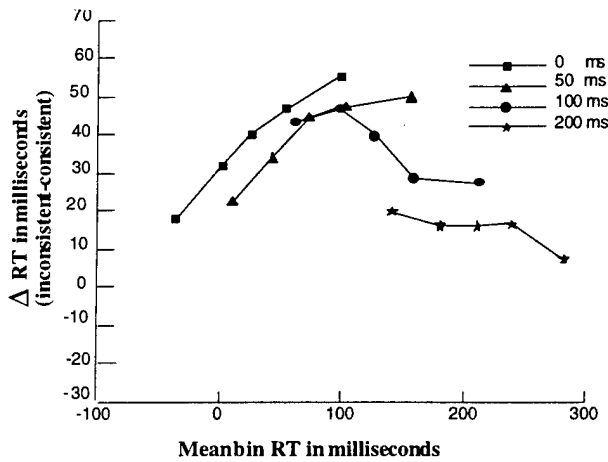


Figure 11. Distributional plots for the Type 3 conditions in Experiment 1 (SOA = 0-200 ms).

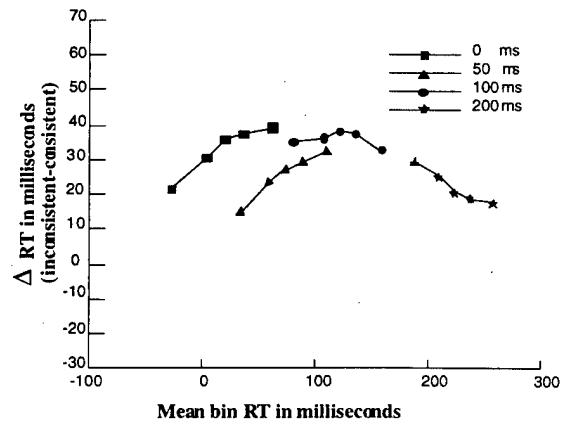


Figure 12. Simulated distributional plots for the Type 3 conditions in Experiment 1 (SOA = 0-200 ms).

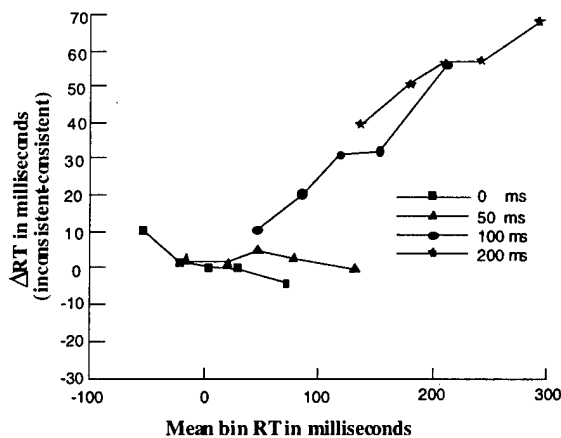


Figure 13. Distributional plots for the Type 4 condition in Experiment 1 (SOA = 0-200 ms).

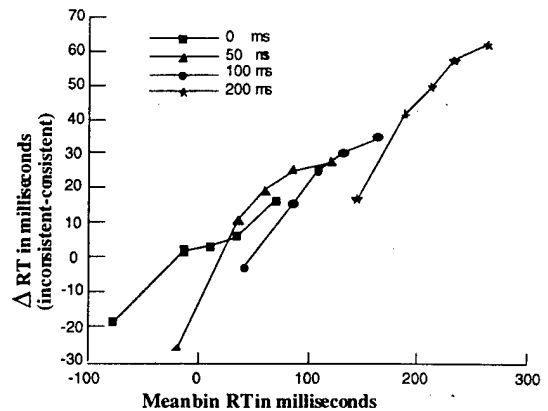


Figure 14. Simulated distributional plots for the Type 4 conditions in Experiment 1 (SOA = 0-200 ms).

### III.2 - Going after the S-S and S-R constituents of Type 8 ensembles.

According to the model's taxonomy, Type 8 ensembles overlap on all three stimulus/response relations: S-R relevant, S-R irrelevant, and S-S (for example, consider a trial in a Stroop task in which the word RED is presented in blue and the subject's task is to name the color). Given that each of these relations has its associated processing consequences in the model, one would expect to be able to observe these consequences in the empirical data. However, this has been difficult to do from published data because: a. in the standard Stroop task, in which the S-R mapping instructions are congruent, there is an *inherent confounding* between these three overlaps (see Table 2 - conditions A and B); b. even when the mapping instructions are *incongruent*, the tasks used are *two-choice* tasks which, because two-choice is a degenerate case of choice, do not generate the requisite data; and 3. even if the tasks were more than two-choice, there has not been sufficient awareness of, or interest in this problem to motivate investigators to report the appropriate data.

The confounding in congruent Stroop tasks can be eliminated with *incongruent* S-R mapping instructions which *severs the correspondence, but not the correlation*, between the relevant stimulus and the response. Thus, with *incongruent* mapping, when the irrelevant S-S relation is consistent (S-S<sup>+</sup>), the irrelevant S-R relation is necessarily inconsistent (S-R<sup>-</sup>), as in row C of Table 2; and when the S-S relation is inconsistent (S-S<sup>-</sup>), the S-R relation is consistent (S-R<sup>+</sup>), as in row D of Table 2. Simon and Sudalaimuthu (1979) were the first to use incongruent S-R mapping instructions with a two-choice Stroop task. They found that irrespective of the S-R mapping, RT was faster when the relevant and irrelevant stimuli matched (S-S<sup>+</sup>) (rows A and C in Table 2) than when they did not match (S-S<sup>-</sup>) (rows B and D in Table 2). Similar results have been obtained with other two-choice, Stroop-like tasks that used non-color stimuli and responses (Green & Barber, 1981; Kornblum, 1992). This apparent *reversal of the S-R consistency effect*, which is similar to Hedge & Marsh's (1975) result with Type 5 tasks, was surprising, and would seem to support an S-S over an S-R (early vs. late) account of the Stroop effect.

However, there is another possible explanation that needs to be considered. Note that coinciding with each instance of the S-S<sup>+</sup> conditions that produced the faster RTs (rows A and C in Table 2), the values of S-R congruence and S-R consistency are identical in each of the two rows: congruent/consistent in row A, and incongruent/inconsistent in row C. Thus, if subjects had used a *rule* (identity/reversal - same/different) to arrive at the correct response from the relevant stimulus, they might have used the *same rule* to deal with the irrelevant stimulus and the response, and possibly have been faster in rows A and C than in rows B and D on that account. This, of course, is an application of Hedge and Marsh's (1975) *logical recoding hypothesis* to the Stroop task. Thus, even though it might have seemed that, in principle (and in spite of the

correlation that remained), the confounding that we pointed to at the beginning of this section would be resolved by using incongruent S-R mapping instructions, a new confound has emerged, and there is no way to disentangle the S-S account from the logical recoding hypothesis on the basis of two-choice tasks even though congruent and incongruent S-R mapping instructions are being used. In order to resolve this issue a minimum of three choices are required; the third choice adds the condition illustrated in Row E, in Table 2.

If *logical recoding* accounted for the results, then the RT in rows C ( $SR^-/SS^+$ ) and E should not differ significantly from each other, because *the same rule*—reversal—is applicable in both conditions; if *S-S consistency* accounted for the results, then there should be a significant difference in RT between rows C ( $SR^-/SS^+$ ) and E ( $SR^-/SS^-$ ), with the RT in rows E ( $SR^-/SS^-$ ) and D ( $SR^+/SS^-$ ) not being significantly different.

We, therefore, conducted a four-choice study with *Type 8* ensembles in which the relevant and irrelevant stimuli consisted of the same carrier-type (i.e. they were both either words, or colors, or digits in order to preclude a “race” based on stimulus modality); the relevant stimuli were presented in the center and the irrelevant stimuli in flanker-like arrangement. There were two S-R mapping instructions: congruent and incongruent. The interesting data came from the incongruent condition. The confounding that is ordinarily found in these tasks, and the logic underlying our argument for the unconfounded conditions are best seen on Table 2, where we also present illustrative data from this study. (The study is fully described in Zhang, H. & Kornblum (in press)).

	<u>Response</u>				<u>Consistency</u> <u>values</u>	<u>RT</u>
	<u>Relevant S</u> <u>color</u>	<u>color-</u> <u>name</u>	<u>Irrelevant</u> <u>S color</u>	<u>Mapping</u>		
<u>Condition</u>						
A	Blue	Blue	Blue	Cong (+)	SR+/SS+	425
B	Blue	Blue	Green	Cong (+)	SR-/SS-	448
C	Blue	Green	Blue	Incong (-)	SR-/SS+	656
D	Blue	Green	Green	Incong (-)	SR+/SS-	679
E	Blue	Green	Red	Incong (-)	SR-/SS-	713

Table 2. The different conditions in a four-choice Type 8 (Stroop) task, with illustrative examples, and experimental results (B.3.2).

The results are clear. First, we note that the RT for condition C ( $S-R^-/S-S^+$ ) is faster than for condition D ( $S-R^+/S-S^-$ ). This is in agreement with the findings in the two-choice literature (Green & Barber, 1981; Kornblum, 1992; Simon & Sudalaimuthu, 1979), and is attributable either

to the effect of S-S consistency dominating over the effect of S-R consistency, or to logical recoding (Hedge & Marsh, 1975). It also raises the question of whether S-R consistency has any effect at all—some have maintained that it does not (e.g. Stoffels, van der Molen, & Keuss, 1989). This last question is answered by comparing condition D ( $S-R^+/S-S^-$ ) with condition E ( $SR^-/SS^-$ ), for those conditions differ only in terms of S-R consistency. The fact that condition E ( $SR^-/SS^-$ ), in which SR is inconsistent, is slower than condition D ( $S-R^+/S-S^-$ ), in which S-R is consistent, indicates that S-R consistency does have an effect in the Stroop task, contrary to what Stoffels et al. (1989) would maintain. Similarly, the fact that condition E ( $S-R^-/S-S^-$ ) is slower than condition C ( $S-R^-/S-S^+$ ) indicates that S-S consistency also has an effect in the Stroop task, and that “logical recoding”, while it may be occurring, is not the whole story. Furthermore, the effects of S-S and S-R consistency obtained in the incongruent Stroop task are *not additive*, for a simple additive model would require the RT difference between conditions A and B to be the sum of SS and SR consistency effects, 91 ms (57 plus 34 ms). But the actual difference is 23 ms ( $t(7)=37.359$ ,  $p<.001$ ). We, therefore, concluded that the Stroop effect is attributable to *both* S-S and S-R consistency, and that the results are consistent with the interdependence of the stimulus and response stages in these tasks, as we argue in DO-'97.

### III.3 - A non-spatial Type 5 task.

The only and, by default, best known example of a Type 5 ensemble in the literature is the one originally used by Hedge and Marsh (1975). The relevant and irrelevant stimulus dimensions were color and spatial position; this was also true of the response dimensions. All subsequent Type 5 studies used these identical dimensions, and all the explanations that have been offered - none of them satisfactory - (Brebner, 1979; DeJong et al., 1994; Hasbroucq & Guiard, 1991; Hedge & Marsh, 1975; Simon & Sudalamaithu, 1979), are based on these observations. According to the DO model, Type 5 tasks owe their particular properties to the relationships between their stimulus and response dimensions (i.e. whether or not they overlap). In order to test the soundness of this generalization, we had subjects perform a Type 5 task in which the dimensions were neither colors, nor positions but overlapped in the prescribed manner.

The stimuli were two-dimensional, and auditory. They consisted of the words “boot” and “gate” presented at either a high or low pitch. (These stimuli were synthetically constructed using Dektalk). The responses were the words “BOOT” and “GATE”, uttered in either a high or low pitched voice. The four subjects in the experiment were voice students at the University of Michigan. Whatever dimension was relevant, the stimulus ensemble was always the same: each of the two words presented at each of the two pitches. When *word* was relevant, subjects had to respond appropriately to the word, regardless of the pitch in which it had been presented. When the mapping was, the response consisted of repeating the word that had just been presented

(boot to boot, and gate to gate); when the mapping was *incongruent*, the response consisted of saying the other word (boot to gate, and gate to boot). Each response word had to be uttered in either a high or low pitch. This meant that on some randomly selected trials the pitch of the stimulus was *consistent* with that of the response (S-R consistent), and on other trials it was *inconsistent* (S-R inconsistent). This was true regardless of the mapping. When pitch was the relevant dimension, the same relations held but for the opposite dimensions.

There were four conditions: pitch relevant/word irrelevant, and word relevant/pitch irrelevant; each of these was run with congruent and incongruent S-R mapping instructions. The results are presented on Table 3 and are clear cut: Whether

<u>Relevant Dimension</u>	<u>Irrelevant Dimension</u>	<u>Mapping</u>	
		<u>Pitch-Congruent</u>	<u>Pitch-Incongruent</u>
Pitch	Word-Consistent	447	541
	Word-Inconsistent	469	498
Word		<u>Word-Congruent</u>	<u>Word-Incongruent</u>
	Pitch-Consistent	431	595
	Pitch-Inconsistent	478	522

Table 3. The relevant and irrelevant stimulus dimensions, S-S/S-R consistency, and S-R mapping conditions used in the non-spatial Type 5 task (III.3). The numbers are the RT obtained.

pitch or word is relevant, when the mapping is congruent, the S-R consistent trials are faster than the S-R inconsistent trials. When the mapping is incongruent, the opposite is the case: S-R inconsistent trials are faster than S-R consistent trials. In other words, we obtained the equivalent of the “reverse Simon effect” *with non-spatial dimensions* under conditions that are logically in the dimensional sense, equivalent to those used by Hedge and Marsh (1975) and their followers. Note too, that the *asymmetry* that is usually reported for such tasks vanished, which suggests that when the level of DO is equally high for the two dimensions in the task, they each exert similar effects when they are made irrelevant. These findings validate the DO model’s dimensional analysis of this and other tasks, and by implication, of the model’s taxonomy.

#### III.4 - Automatic response activation in go/nogo tasks

The DO model postulates two routes in the generation of the response in SRC tasks: one, the *controlled* route, identifies the correct response in accordance with the S-R mapping.

instructions; and the other, the *automatic* route, triggers the response that corresponds to the stimulus that was presented. In principle, this processing architecture is equally applicable to go/nogo tasks where the response is known and well prepared in advance, on every trial.

In particular, if when presented with a stimulus, the subject is able to *categorize* that stimulus as a go signal, and he has *fully prepared* the response to be made on go trials, then he can make that response even *before* being able fully to identify that stimulus. If the stimulus and response sets in this task have dimensional overlap, then, according to the model, a stimulus - when presented - will automatically activate its corresponding response - just as in the choice task. If that response is the one that the subject has prepared, then it will be executed rapidly and accurately. However, if it isn't, then further processing is required which will increase the RT. The difference in RT for the *very same* response when produced by these *two different go stimuli* would be an S-R congruence, or S-R compatibility effect. This prediction was tested using a go/nogo task where, on every trial, subjects were fully prepared in advance to make the response that was called for by the go signal. All the responses were verbal.

In one condition the set of go signals consisted of two digits (4, 8). The set of *nogo* signals either came from the *same category*, i.e. digits (2,6), or from a *different category*, i.e. symbols (\*, #); these nogo conditions were run blocked. Prior to any one trial, subjects were *fully prepared* to say either the digit-name FOUR or the digit-name EIGHT irrespective of what the go signal was. Thus, for example, if the subject had prepared to say FOUR, and a 4 came up as the go signal, the response was congruent; however, if an 8 came up, then responding with FOUR was incongruent. The results were clear (see Figure 15): the RT for congruent responses was faster than for incongruent ones. This difference was greater (41 ms vs. 21 ms.) when the nogo signals came from the same category (2,6) than when they came from a different category (\*, #). In another very similar condition, where the go signals consisted of colors, the responses of color-names (that could be either congruent or incongruent with the go signals), and the nogo signals either came from the same (other colors) or different (\*, #) categories, the results were practically identical (Kornblum & Zhang, 1995).

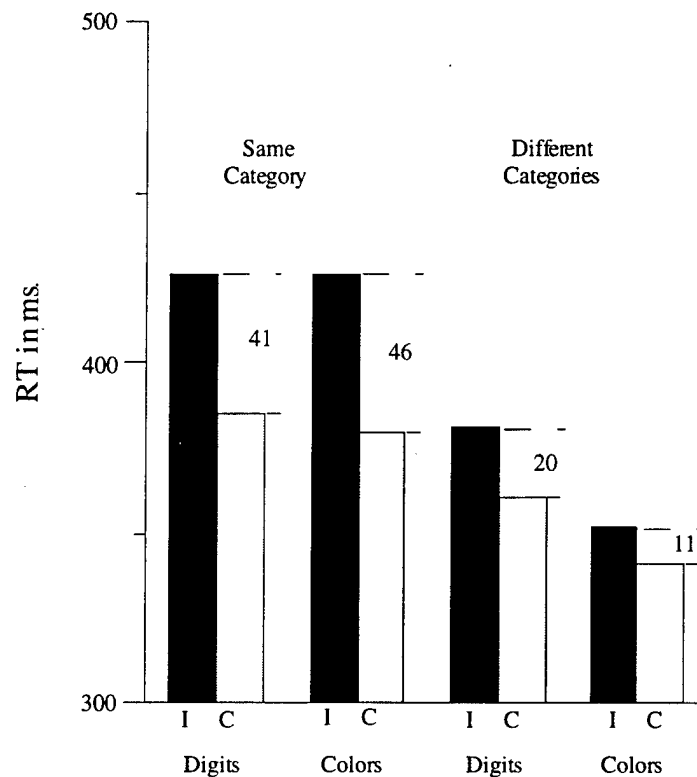


Figure 15. Reaction times for consistent (c) and inconsistent (I) trials in the go/nogo experiment (III.4) when the go and nogo signals are in the same or in different categories, for digit and color go stimuli..

These results are important supporting evidence for the automatic response activation hypothesis of the DO model. Note that the magnitude of the congruence effect differed depending on whether the go and nogo signals overlapped: if they did, i.e. if they both came from the same category, the effect was larger than if they didn't. This suggests that the congruence effect is being modulated by the degree to which the stimulus on any one trial needs to be identified: if the go/nogo decision can be made on the basis of the *category membership* of the stimulus, which is the case when the go and nogo signals belong to different categories, then detailed identification of the individual stimulus is unnecessary and the congruence effect is small. If, on the other hand, the go/nogo decision requires *identification* of the individual stimuli, which is the case when the go and nogo stimuli belong to the same category, then the congruence effect is relatively large.

### III.5 - Validating S-S consistency effects with a go/nogo task.

Even though we have shown (e.g. in III.1 above) that S-S and S-R consistency effects have different time courses, it could be argued that what *appears* as a distinction between S-S and S-R consistency effects is in fact a difference in degree, and not in kind (e.g. Lu & Proctor, 1995).



We addressed this issue more directly than in III.1, in this next experiment by using a task from which the S-R consistency component had been *omitted*.

We used a key-pressing, go/nogo task with a Type 4 ensemble; i.e. an ensemble with S-S overlap *and no* S-R overlap. The stimuli consisted of the words "BLUE", "GREEN", "DETAIL" and "NOVEL", presented in blue or green. Color was relevant, words were irrelevant. That is, subjects were instructed to press the key if, for example, the stimulus was the color green, and to withhold their response otherwise. The irrelevant words "BLUE" and "GREEN" overlapped with the color (Type 4), thus generating S-S consistent/inconsistent trials; the words "DETAIL" and "NOVEL" were, presumably, neutral with respect to both the relevant stimulus and the response. The critical variable was color saturation which took on three values: most saturated, medium saturated, and least saturated. Our assumption was that the less the saturation, the more difficult the discriminability, hence the longer the RT. The object of this exercise was to *lengthen* the RT. This assumption was borne out by the RT for the neutral words, which increased as saturation decreased (see Table 4). Of greater importance, however, is the finding

	<u>S-S</u>		<u>S-S</u>
	<u>Consistent</u>	<u>Neutral</u>	<u>Inconsistent</u>
A (Least saturated)	357	372	388
B (Medium saturation)	314	324	322
C (Fully saturated)	279	282	281

Table 4. RT results of the the go/nogo experiment (III.5).

that *consistency interacts with saturation*; i.e. the S-S consistency effect is highly significant with low color saturation (Condition A, 31 ms), and vanishes with high saturation (Condition C). This is in precise accord with the predictions of the model. In particular, when stimulus discrimination is *easy*, the relevant stimulus activation function rises steeply thus greatly attenuating the potential modulation by the irrelevant stimulus activation function, and in fact constraining it to the *early* part of the process. When, on the other hand, stimulus discrimination is difficult, and thus time consuming, the relevant stimulus activation function rises more slowly, thus prolonging the stimulus processing stage, and allowing the irrelevant stimulus activation function to exert a greater differential effect (recall that this effect is integrated over time) depending on whether it is consistent or inconsistent (see Figure 4).

### III.6 - Negative priming and SRC: *Intertrial* evidence for automatic response activation

Negative priming (NP) effects have been broadly cited as evidence for the existence of inhibitory mechanisms in selective attention (e.g. Neill, 1977; Tipper, 1992). Typically the negative priming procedure requires *pairs of trials*. On the first trial, subjects are asked to identify a target object while ignoring a simultaneously presented distractor object - call this the *prime trial*. If on the second trial - call this *the probe trial* - the target is the object that was previously presented as the distractor, then the RT to this probe target is considerably longer than if it had been presented anew. This is called *negative priming* because the presentation of a stimulus on two consecutive trials causes *interference on the second presentation*. It is assumed that this interference is the result of a conflict between target and distractor during the prime trial; i.e. that the inhibition of the distractor during the prime trial is carried over to the probe trial, even though the distractor may not have produced any observable interference on the prime trial (Driver & Tipper, 1989).

According to the DO model, the presentation of a stimulus element in Type 2 tasks automatically activates its corresponding response. If, because of incongruent S-R mapping instructions, this response is not the correct one, then it must be inhibited. Thus, even though there are no distractors in Type 2 tasks, irrespective of the mapping, the model postulates that when the mapping is incongruent a *conflict* is generated, followed by a resolution which is mediated by an *inhibitory process* - much like what is postulated to occur during negative priming. If the inhibitory mechanisms in these two experimental paradigms (SRC and NP) have similar properties, then one should be able to produce negative priming effects using *incongruent* Type 2 conditions as *prime* trials. Furthermore, if negative priming is obtained under these conditions, it would also greatly strengthen one of the DO model's central tenets - the automatic response activation hypothesis - and extend its scope from intra- to inter-trial effects.

We tested this prediction in two studies (Shiu & Kornblum, 1996 a, and b) in which subjects made incongruent naming responses to words and picture stimuli presented on alternate trials (prime/probe). On some trial pairs (the NP pairs) the *correct* response on the probe was *the same* as the response that had to be *inhibited* on the prime. On other trial pairs (*the control pairs*) there was no such relation although the S-R mapping was incongruent for all pairs. We found that the probe RT for NP pairs was significantly longer than the probe RT for control pairs. This finding has important implications for the DO model, as well as for the understanding of SRC tasks and negative priming.

This result provides strong evidence for the automatic activation, and subsequent inhibition of the congruent response as postulated by the DO model's automatic response activation hypothesis. It also demonstrates that *covert* response conflicts, without distractors, are sufficient to produce negative priming effects. Even though these findings are easily

explicable in terms of the DO model's automatic response activation hypothesis, they pose a serious challenge to other hypotheses that have been proposed as general accounts of negative priming; in particular, the feature mismatch and the episodic retrieval hypotheses (e.g. Fox, 1995).

Given that NP effects are found in Type 2 incongruent mapping tasks, the mapping effect (i.e. the difference in RT between congruent and incongruent mapping) needs to be reexamined, for it includes a NP component. Of course, NP cannot possibly account for the *entire* mapping effect because the former is much smaller than the latter. Nevertheless, it appears to be a significant constituent of the mapping effect and suggests that a reanalysis of archival data might be very fruitful indeed.

SRC and selective attention are often treated as two separate areas of research even though similar tasks have been studied in both areas (e.g. the Stroop task). This NP study seems like the start of a fruitful dialogue between the two areas.

#### IV. METHODS AND PROCEDURES

This section on methods & procedures deals with the general characteristics of the experiments that we have just summarized. All the experiments were variants of the choice reaction-time paradigm.

##### A. Structure of a Typical experiment

A typical experiment included several consecutively run *sessions* for each subject. Ordinarily the first session served to instruct and practice the subjects on the assigned task with subsequent sessions being used to collect the desired test data. This arrangement allowed the subject's performance to stabilize and also reduced variability. One session lasted for approximately one hour and was divided into several *blocks* of trials. Each block consisted of approximately 30 to 40 trials, with feedback being provided after each trial, and/or block as needed. Some blocks were self-contained, in that all the experimental factors were balanced within it, others were segments from a longer *series* of trials within which the balancing had been accomplished. Subjects ordinarily initiated the start of a new block and were encouraged to rest between blocks. Whenever we switched from one experimental condition to another, the subjects received at least one warm-up block for which the data were excluded from the analysis of the results. This procedure minimized any possible contamination between successive experimental conditions.

The time-line for a *standard* trial began with a warning signal, which was followed by a stimulus, to which a response was then made. The stimuli were response-terminated; feedback was sometimes given after each trial, and sometimes only at the end of a block of trials. In

experiments with SOAs an additional signal was introduced between the warning signal and the stimulus. That stimulus could be, but need not have been, correlated with the stimulus or the response.

## 2. Subjects

Subjects in these experiments were university student volunteers who were paid \$5.00 per hour for their participation. We carefully controlled the handedness, sex, color vision, visual acuity, hearing, and other ancillary traits of the subjects.

## 3. Scoring

In addition to their hourly pay rate, subjects earned bonuses determined by their performance. For this purpose a score was calculated at the end of every block, based on the subjects' speed and accuracy for that block. The particular values in the payoff matrix were determined by pilot studies for each experiment. We have found this to be an effective way of keeping subjects highly motivated

## 4. Stimulus and response sets

Because all the experiments addressed issues closely related to the dimensional overlap model the stimulus and response sets that were used all had precisely defined *dimensional relationships* to each other. These are all described in the summaries of the individual experiments.

## 5. Balancing matches, mismatches, and the associations between feature

It is important to note that for ensembles with irrelevant dimensions, where the number of alternative values on the *irrelevant* dimension is the same as on the *relevant* one, the number of possible stimuli increases as the square of the number of alternatives ( $n$ ). This must be taken into account when constructing trial blocks with  $n > 2$ . Consider Type 3 ensembles as an example. Here the irrelevant dimensions will *match* the response for  $n$  different stimuli, and *mismatch* it for  $(n^2 - n)$  stimuli. If all the *possible* stimuli were to be randomly presented in a block it would not only lead to an imbalance in the proportion of matches and mismatches, but in the probability of feature associations (Mordkoff & Yantis, 1991). In constructing blocks of trials from such ensembles, therefore, we used an equal number of matching and conflicting and/or non-matching stimuli. The subset of those mismatching stimuli were selected so that all the values of the relevant and irrelevant dimension were represented, without duplication, in the subset. As  $n$  increases the number of such possible independent subsets increases so that different subsets could and were used in different blocks of trials.

## 7. The data

Our basic data consisted of reaction times and accuracy. Before analyzing the reaction time data we eliminated trials with errors (which were analyzed separately), and trials that immediately followed an error. Our analyses were sometimes done on whole distributions, and sometimes on the first two moments of the distribution. Outliers were identified by an algorithm that takes the actual set of data to be trimmed as its basis for constructing a *hypothetical* distribution which it then compares with the *actual* distribution. Outliers were identified in terms of hypothetical, criterial z-scores. This procedure avoids trimming outliers by arbitrarily selecting high or low cut-off points without regard for the distribution being trimmed.

## B. Basic Apparatus

All our experimental equipment for data collection and analysis was controlled by IBM compatible computers.

**V. PERSONNEL**

	1993-94	1994-95	1995-96	1996-97
<hr/>				
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D. Graduate Students:				
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E. Computer Programmer/ Engineer:				
<b>Tony Whipple</b>	.25	.5	1.00	1.00
F. Lab Assistants	.5	.5	.5	.5

**VI. PUBLICATIONS (During Grant Period: November 1, '93 – October 31, '97).**

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1. Shiu, L-P, and Kornblum, S. Stimulus-Response compatibility effects in go/no-go tasks: Evidence for a dimensional overlap model. Perception and Psychophysics.
2. Kornblum, S., Stevens, G., Whipple, A., & Requin, J., The effects of irrelevant stimuli I: The time course of S-S and S-R consistency effects in DO Types 3, 4, and 7 tasks. Journal of Experimental Psychology: Human Perception and Performance.
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- Zhang, H. (1994). Stimulus-stimulus and stimulus-response compatibility: and interactive activation model. Doctoral dissertation, The University of Michigan, Ann Arbor.

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3. Zhang, J., Riehle, A., Hohnke, C., Requin, J., and Kornblum, S. (1994) Single neuron response and sensory-motor processing. Presented at the Cognitive Neuroscience Society Meeting, San Francisco, March 27-29.
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